

Design of 2MHz OOK transmitter/receiver for inductive power and data transmission for biomedical implant

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Article Info

Article history:

Received Jan 24, 2019

Revised Mar 11, 2019

Accepted Mar 21, 2019

Keywords:

Biomedical implants

Class E power amplifier

Inductive link

OOK modulation/demodulation

Transmitter/receiver

Voltage regulator

ABSTRACT

In this work a 2 MHz on-off keying (OOK) transmitter/receiver for inductive power and data transmission for biomedical implant system is presented. Inductive link, driven by a Class E power amplifier (PA) is the most PA used to transfer data and power to the internal part of biomedical implant system. Proposed transmitter consists of a digital control oscillator (DCO) and a class E PA which uses OOK modulation to transfer both data and power to a biomedical implant. In proposing OOK transmitter when the transmitter sends binary value "0" the DCO and PA are turned off. With this architecture and 2 MHz carrier wave we have implemented a wireless data and power transfer link which can transmit data with data rate 1Mbps and bit error rate (BER) of 10⁻⁵. The efficiency of power transfer is 42% with a 12.7 uH transmitter coil and a 2.4 uH receiver coil and the power delivered to the load is about 104.7 mW. Proposed transmitter is designed for output power 4.1V. OOK receiver consists of an OOK demodulator, powered by rectified and regulated 5V p-p RF signal across the receiver coil. The supply voltage of proposed voltage regulator is 5 V with 9mV/V line regulation of. All circuits proposed in this paper were designed and simulated using Cadence in 0.18 um CMOS process.

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1. INTRODUCTION

Biomedical implants are widely used in our everyday life, for example, cochlear implant system is an electronic implant that aims to severe hearing loss and for people with tinnitus or provide a certain level of hearing for some people with profound deafness (deep end cochlear deafness). As shown in Figure 1, the working of a cochlear implant is as follows, a speech processor used to select and arrange sounds picked up by the microphone, a receiver and transmitter convert received signals sent by the speech processor into electric impulses, a microphone, picks up sound from the environment, and an electrode array, which is a group of electrodes sends the impulses to different regions of the auditory nerve collected from the simulator [1, 2].

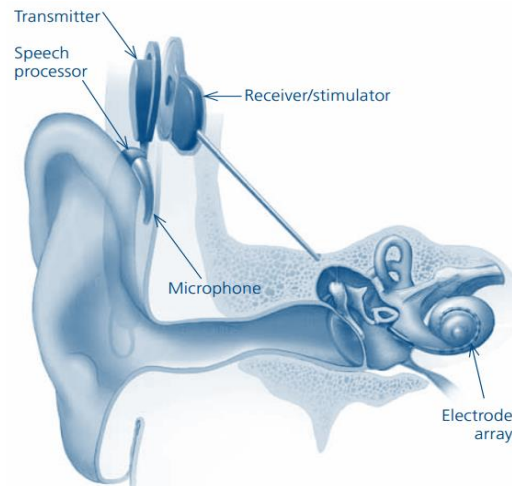


Figure 1. Ear with cochlear implant

In general, biomedical implant system has two different parts, an external part or transmitter (outside the human body) and an internal part or receiver (inside the human body). A biomedical implant system use inductive powering to transmit both data (modulated signal) and power from the external part to the internal part [3-5]. A power amplifier (linear, class-E PA...) is used to generate a magnetic field in a coil of the transmitter, placed on the skin. This magnetic field induces an AC current in another coil of the receiver. The generated AC voltage in the coil of receiver is rectified and regulated by a voltage regulator circuit and used as supply voltage for the inner circuit blocks of the receiver (demodulator, clock generator...). To transfer power to the implant, it is required to transmit/receive data from/to the implant and communicate with the implant. In the implants that are used to apply artificially acquired sensory information to the peripheral or central nervous system, like retinal prostheses and cochlear implants, a large of digital data should be transmitted to the implant; it is preferable to use the same inductive link to transfer power. The data rate transmission in this sort of biomedical implant system should be high, exceeding 20Mbps for visual prostheses and 1Mbps for cochlear implants.

Because the high tissue electromagnetic absorption at higher frequencies as well as the coupled coils self-resonance, the wide bandwidth with a carrier frequency is limited to a few ten of Mega Hertz. To increase the data transmission rate for the biomedical implants, two separate pairs of coils for data and power transfer are used, a pair of high-Q power coils are used for data transfer, and another pair of coils (power coils) are used for power transfer. The data are transmitted using a frequency sinusoidal signal which has a much larger frequency than the signal used to transmit power, or using a carrier-less data modulations such as PDM modulation (pulse delay modulation) and PHM modulation (pulse harmonic modulation) [6-8].

On the aspect of bandwidth of this inductive transcutaneous link a few studies that focus. The mostly modulations used in the radio frequency transceiver sensor node are On-off keying modulation (OOK), Amplitude shift keying modulation (ASK) and frequency shift keying modulation (FSK) [9, 10]. Because of their simple modulation/demodulation circuitry OOK and ASK modulation have been used in the above applications, and they are suitable for envelope detection and simple super-regenerative architecture [11, 12]. The implementation of ASK is another work that we published in [13]. In this work we are particularly interested by the OOK transmitter/receiver with 2 MHz for medical implant with 1 Mbps data rate. Our work is designed in 0.18 μm CMOS technology. To minimize the power consumption of the proposed OOK transmitter, tower blocks are used to generate an OOK signal, a digital control oscillator (DCO) and a class E power amplifier (PA). In this proposed architecture according to the binary value transmitted the OOK transmitter can be realized by turning on/off the DCO circuit and the class E PA. The class E PA with high efficiency provides the required power for signal transmission. The OOK transmitter was designed for output power 4.1V and 1.2mA power consumption from 4V supply voltage. On the other hand, the OOK receiver consists of an OOK demodulator, voltage rectifier and voltage regulator. OOK demodulator is powered by a 5V supply voltage, rectified (rectifying of the RF signal at the receiver coil, 5V OOK waveform) using NMOS bridge voltage rectifier and regulated using voltage regulator. The organizing of this paper is as follows: section 2 presents the generic architecture of an inductive link. Analyzes and theoretical calculates of 2 MHz OOK transmitter, 2 MHz receiver and simulation results/discussion are presented in Sections 3, 4 and 5 respectively.

2. INDUCTIVE LINK

An inductive link is an air core transformer works on the principle of mutual coupling .It consists of primary and secondary circuits. As shown in Figure 2 the primary circuit of inductive link tuned in series resonance and secondary circuit tuned in parallel resonance. If a power amplifier is used in the primary circuit the inductive link is an ideal combination due to its close resemblance to the actual link. In addition, because the capacitor voltage and phase of the inductor cancel at resonance a series resonant primary network requires lower voltage is swinging at the input of primary network of inductive link. Voltage gain and efficiency profiles for this topology shown in Figure 3 are described mathematically by (1) and (2) respectively [14].

$$\frac{V_{in}}{V_{RL}} = \frac{\omega^2 m C_{1S} R_L}{[(d C_{2P} R_L) \omega^4 + j(e-d) \omega^3 + (f C_{1S} + g R_L C_{2P}) \omega^2 + j(c R_{L1} C_{1S} + h) \omega + c]} \tag{1}$$

$$n_{link} = \frac{\omega^2 M^2 R_L}{[(a + R_L^2 C_{2P}^2) \omega^2 + (b + c M^2) \omega^2 + C^2 R_{L1}]} \tag{2}$$

with RL load resistance.

- $a = R_{L1} L_2^2 + R_{L2} M^2$
- $b = R_{L1} R_L^2 (C_{2P}^2 R_{L2}^2 - 2 C_{2P} L_1) + L_2^2 R_{L2}$
- $c = R_{L2} + R_L$
- $d = C_{1S} (M^2 - L_1 L_2)$
- $e = C_{1S} C_{2P} R_L (L_1 R_{L2} + L_2 R_{L1})$
- $f = L_1 R_{L2} + L_2 R_{L2} + L_1 R_L$
- $g = R_{L1} C_{1S} R_{L2} + L_2$
- $h = R_{L2} C_{2P} R_L + L_2$

If the circuit is resonated at resonance condition ($jLw = 1/jCw$) this model produces best results.



Figure 2. Inductive link topology

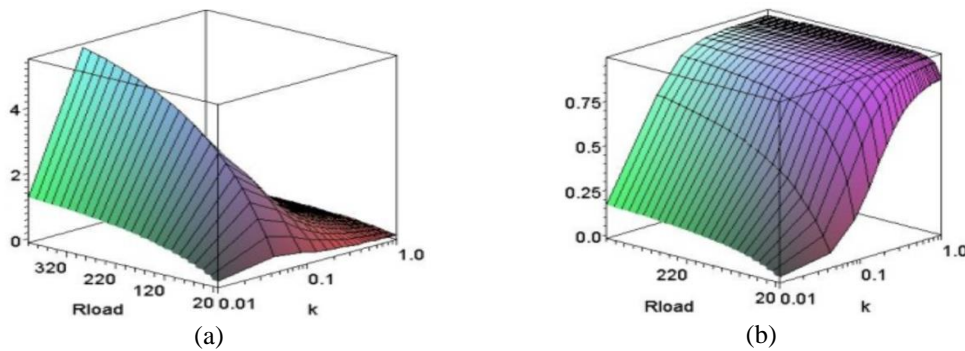


Figure 3. (a) Voltage gain, (b) efficiency of inductive link topology shown in Figure 2

3. TRANSMITTER STRUCTURE

The block diagram of the proposed OOK transmitter is shown in Figure 4. The 2 MHz OOK modulation scheme is utilized, in which binary values “1” and “0” are represented by a pulse and no pulse transmission respectively [15, 16]. The OOK transmitter consists of two principal blocks: the oscillator circuit and the power amplifier. According to message data the OOK transmitter can be realized by turning on or off the power amplifier and digital controlled oscillator. In proposing transmitter when digital controlled oscillator is turned off, the power amplifier is turned off, too. The digital control oscillator and power amplifier are represented in Sections 3.1 and 3.2 respectively.

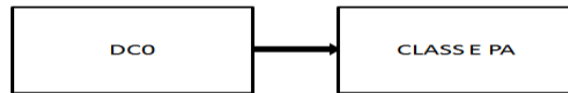


Figure 4. Proposed OOK transmitter

3.1. Digital control oscillator DCO

Circuit oscillators play a key role in a wireless communication network. In OOK transmitters, oscillator and power amplifier turn off in sending of binary “0”. However, all of components of the transmitter must be switched on and off with data rate frequency. The required time of ON/OFF duration of all the blocks determines the maximum data rate frequency. The required time for the ON/OFF duration of oscillator is higher than the other blocks of OOK transmitter. Figure 5 shows the LC complementary oscillator used in proposed transmitter. It composes of the digital signals that are adopted to control. The C bank has 5 transistor switches with capacitors and generates thirty two overlapped discrete tuning curves to increase the desired frequency tuning range. The amplitude voltage is given by (3).the amplitude voltage is proportional with bias current and parallel resistance.

$$V_{amp} = \frac{4}{\pi} R_p I_{bias} \quad (3)$$

with the R_p is the equivalent resistance which determined with quality factor of inductor.

In the designed of the proposed complementary oscillator, V_{dd} is 2V and 0.7uH inductor with $Q=25$ and the swing voltage is about 3.5 V that is sufficient for driving modulator. In the complementary oscillator, having a high swing voltage required that parallel resistance R_p or bias current to be high. It should be reminded that high bias current will increase power consuming and large parallel resistance require for an inductor. Unfortunately, the integrated inductor inherently has low quality and R_p could not be higher. Since the oscillator must be having enough output voltage for driving of power amplifier. So, for have high swing output in the oscillator DC current must be increased.

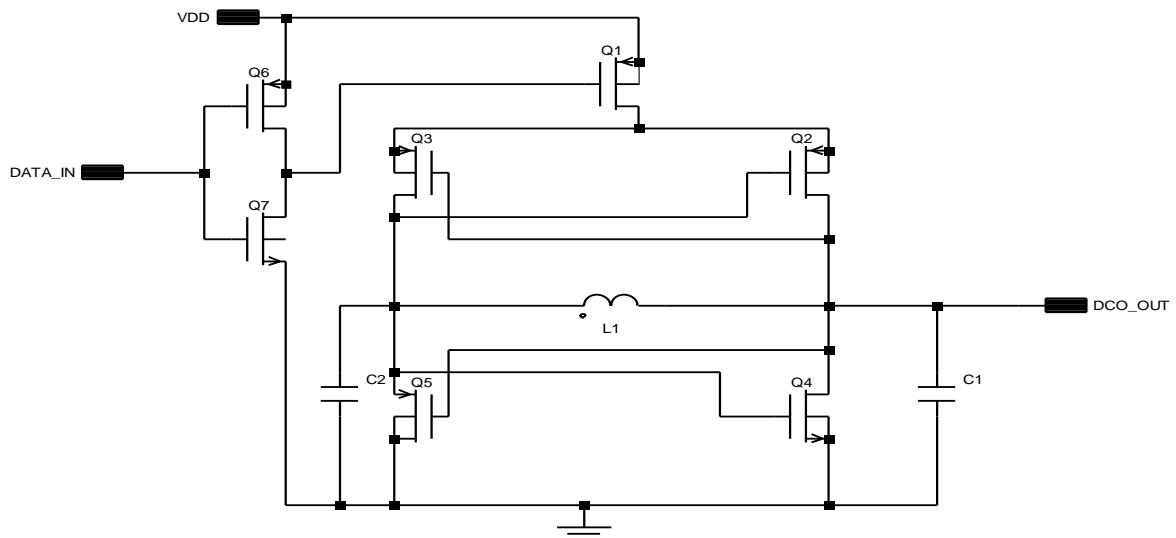


Figure 5. DCO circuit

3.2. Class E power amplifier

Class E power amplifier (PA) is known as switched mode PA because transistor or active device acts as a switch. Classes A, B and C refer to amplifiers in which the active device acts as a current source. Class E PA composed of a single-pole switch (active device) and a load network. To improve the efficiency of power amplifier the active device as the switch is used instead a high-impedance current source. With DC input voltage and current, class E PA is capable to drive relatively high AC current through the coil of

transmitter with high efficiency. This is a consequence of an impedance transformation inherent to the Class E circuit. The maximum achievable efficiencies from different amplifier classes are shown in Table 1. Because of its 100% theoretical efficiency the Class E PA is a preferable designer's choice. Proposed class E power amplifier is shown in Figure 6. To develop Class E Amplifier we employed single ended Class E configuration with multi-frequency load network topology. The advantage of using this structure is the ease of inclusion of parasitic drain-source capacitance of the switch transistor into the design optimization as compared to Class C or Class D amplifiers [17, 18]. The parameters of proposed class E PA are presented in Table 2.

Table 1. Power amplifiers efficiencies

Amplifier type	Maximum efficiency %	Conduction angle
Class A	50	360
Class B	78.5	180
Class AB	<78.5	180-360
Class C	Up to 90	120.6
Class D	80-95	-
Class E	100	Optimum 50%

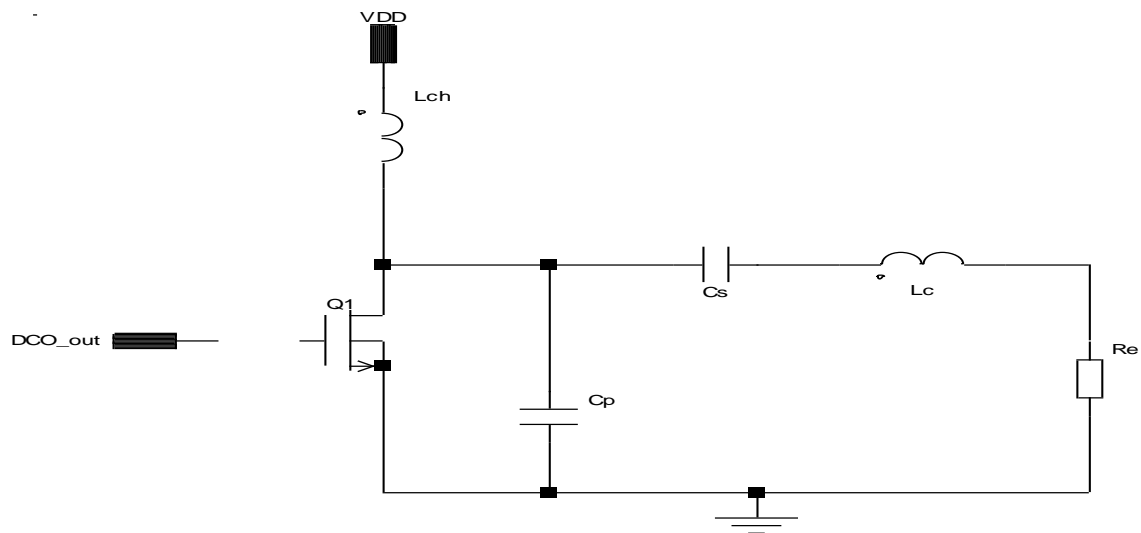


Figure 6. Proposed class E PA

Table 2. Parameters of proposed class E PA

Operating Frequency	2 MHz
Designed for Output Power	4.1V
Supply Voltage	5 V
Inductance – Transmitter Coil L_C	35 μ H
Parallel Capacitor C_P	5 p
Series Resonant Capacitance C_S	100 p
RF choke L_{CH}	40 μ H
Load resistance R_L	127 m

4. OOK RECIEVRE STRUCTURE

The OOK receiver as shown in Figure 7 consists of a voltage rectifier an OOK demodulator and voltage regulator. The RF signal at the coil of receiver is rectified using a bridge rectifier. The regulator circuit comes after the rectifier. The voltage regulator performs two main functions. The first is to regulate the output voltage to a preferred value and a preferred range of the internal part of a biomedical implant system. The other is to protect the inner circuits from breaking at high RF input power. The basic topology of a voltage regulator is shown in Figure 8 [19, 20]. It consists of an OTA (operational transconductance amplifier), tow regulation resistances and a voltage reference to generate a regulated voltage using an input voltage reference auto generated V_{ref} .

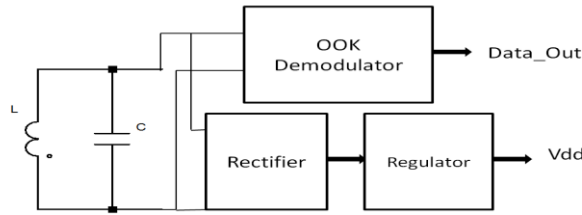


Figure 7. Block diagram of OOK transceiver

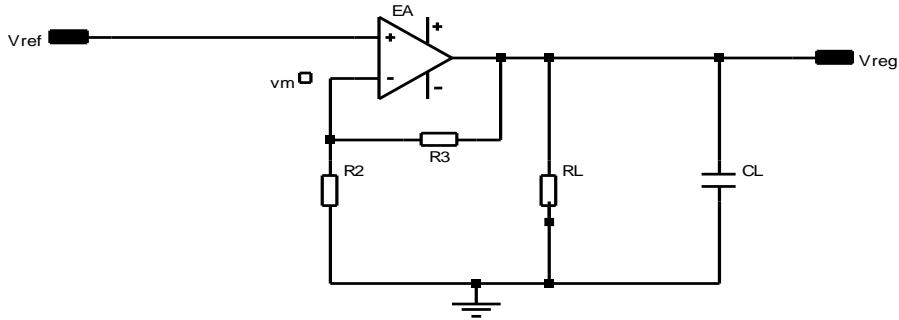


Figure 8. Voltage regulator topology

The output of a voltage regulator V_{reg} is given as follows. In an ideal case considering a finite open-loop gain A_{ol} of the regulated voltage is given by:

$$V_{reg} = A_{ol}(V_p - V_m) \tag{4}$$

with $V_p = V_{ref}$ we can write:

$$V_{reg} = V_{ref} \cdot \left(\frac{1}{\frac{1}{A_{ol}} + \frac{R_2}{R_2 + R_3}} \right) \tag{5}$$

If we consider an infinite open-loop gain for an ideal case so the simplifying calculates can we give:

$$V_{reg} \cong V_{ref} \cdot \left(1 + \frac{R_3}{R_2} \right) \tag{6}$$

In (6) the output voltage of the voltage regulator depends on the voltage reference V_{ref} and resistances R_2 and R_3 .

The operational amplifier (OPA) used instead OTA shown in Figure 9 compares the voltage reference V_{ref} with the feedback signal from V_{reg} before producing an error signal to drive the pass transistor $M1$ for the constant V_{reg} . The feedback signal is generated by a voltage divider, which contains a four diode connected transistors ($M2-M5$) used instead resistances $R2$ and $R3$ [20, 21].

The stability of voltage regulator V_{reg} depends on the bias current I_{SS} of the OPA, as shown in the following equation:

$$\frac{\Delta V_{reg}}{\Delta I_{SS}} = \frac{\left(\frac{r_{on}/r_{op}}{2} \right) g_{m1}(r_{o1}/R_L)}{1 + \left(\frac{g_m R_{4,5}}{R_{4,5} + R_{2,3}} \right) \left(\frac{r_{on}/r_{op}}{2} \right) g_{m1}(r_{o1}/R_L)} \cong - \frac{r_{2,3} + r_{4,5}}{g_{mr} r_{2,3}} \tag{7}$$

Where r_{op} and r_{on} the output resistance of $M1$ and the load resistor, r_{on} and r_{op} are the output resistance of NMOS and PMOS transistor, g_m and g_{m1} are the transconductance of NMOS in the differential pair and $M1$, and $R_{2,3}$ and $R_{4,5}$ are the equivalent resistance of $M2$ to $M5$, respectively. The output of the voltage regulator is regulated to generate a supply voltage $V_{dd}=5V$ independent of the input OOK signal levels. The supply voltage is used to power the inner circuit of the receiver blocks like the demodulator and the clock generator.

Figure 10 shows the proposed OOK demodulator for internal part of biomedical implant. The implant receives control settings from the external transmitter via the inductive link using OOK modulation with a data rate of 1Mbps. The envelope detector extracts the signal from the carrier wave. As the recovery time of the carrier varies with the load and coupling coefficient, the time constant of the RC peak detector should be set to a larger value than the worst case rise time of the carrier [22, 23]. The implemented C is 18.5 pF and R is 1.1 KOhm. Transistors M5–M9 form a Schmitt trigger generates a digital data from the peak detector.

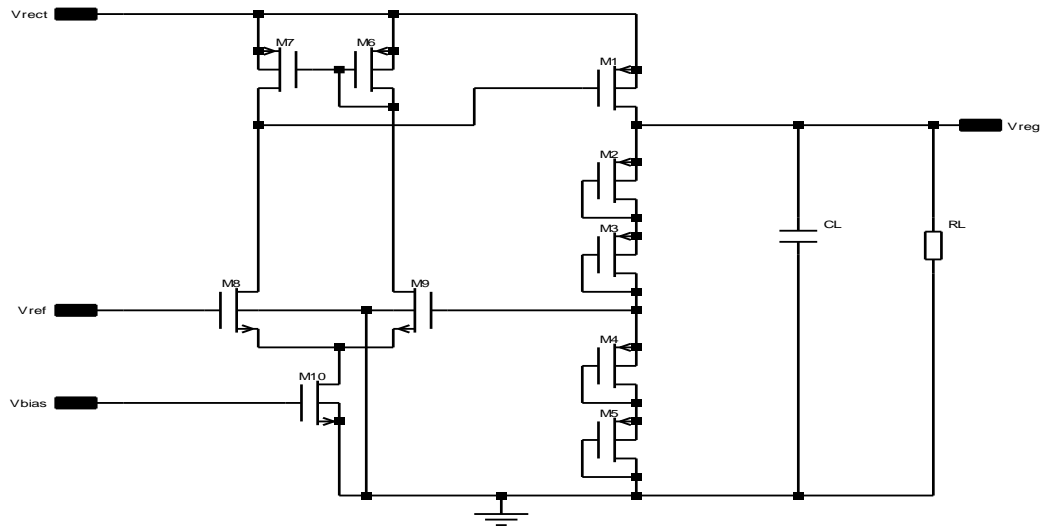


Figure 9. LDO regulator using OPA

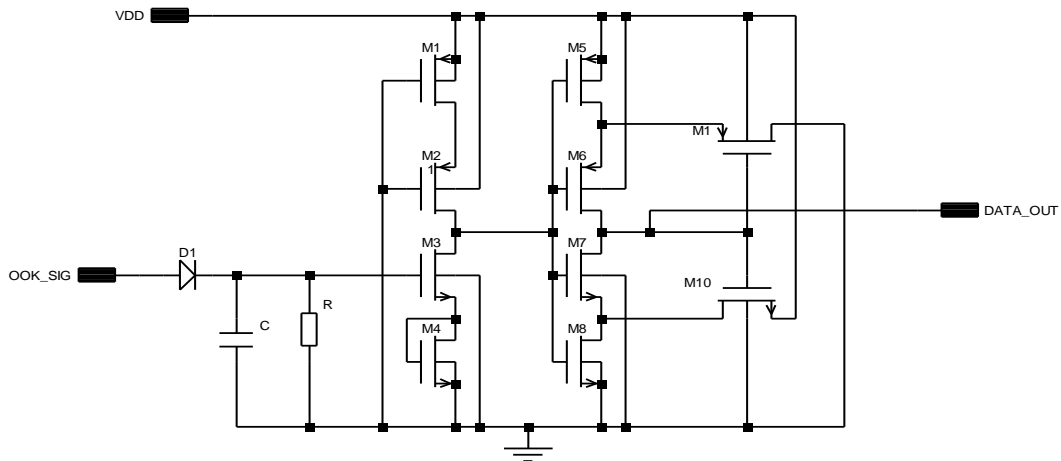


Figure 10. Implementation of OOK demodulator

5. SIMULATION AND RESULTS

The proposed transmitter consists of DCO and power amplifier has been implanted in 0.18 μm CMOS technology. The minimum output of DCO working at 2 MHz is 1.8 V. The waveform of output modulated signal with “00100100100100” binary sequence and 1 Mbps data rate was achieved with 104.7mW output power and 42% link efficiency is shown in Figure 11. Figure 12 and Figure 13 show the voltage across the receiver coil, the amplitude of the OOK waveform at the secondary side is about 5V and the transient response of proposed rectified and regulated voltage with 20 dBm input power, after 2.9 μs the DC voltage is 5.0008 V with line regulation of about 9mV/V respectively. The transient response of OOK demodulator is shown in Figure 14. The proposed demodulator circuit has the ability to decode an encoded signal back to 2 MHz carrier from an OOK modulated radio frequency input signal with 5V amplitude.

Table 3. Performance comparison of OOK transmitter

Work	[3]	[24]	[25]	This work
Power amplifier	Linear	Class E	Class E	Class E
Modulation	FSK	FSK	OOK	OOK
Carrier frequency	5/10	0.48±0.004	5	2
Data rate (Mbps)	2.5	0.12	1.25	1
Process	1.5 um CMOS	1.5 um CMOS	1.5 um CMOS	0.18 um CMOS
BER	10 ⁻⁵	-	-	10 ⁻⁵

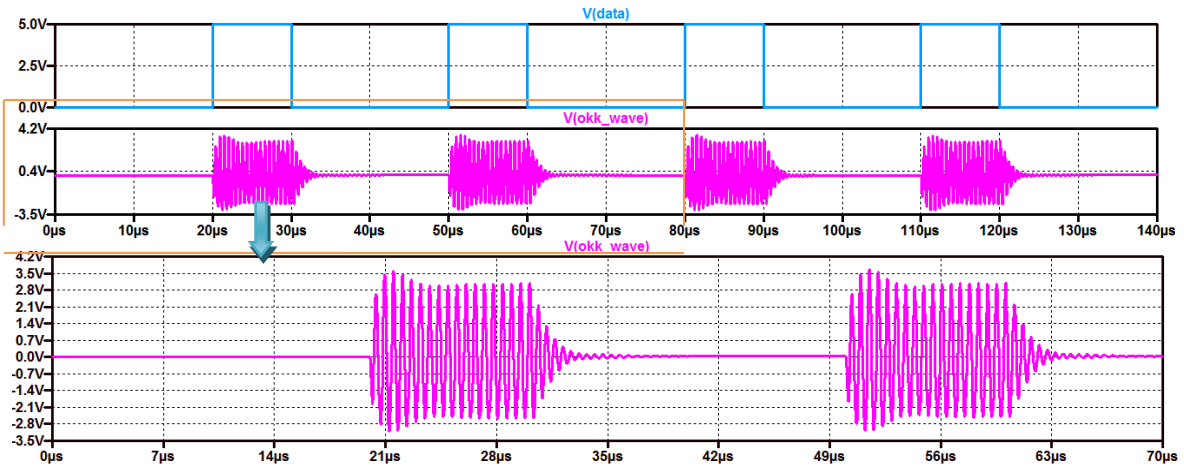


Figure 11. (OOK modulated signal) voltage at the coil of proposed transmitter

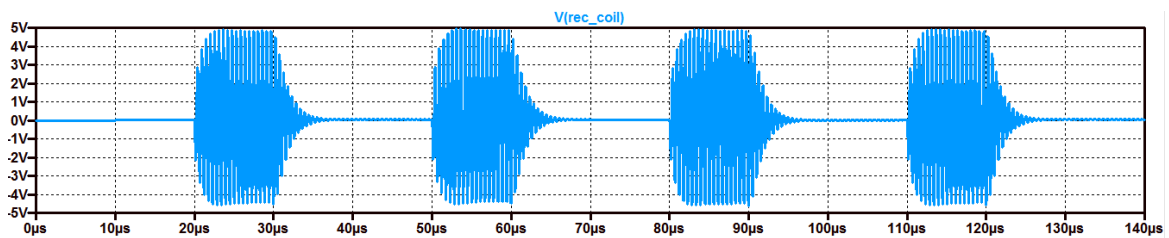


Figure 12. Voltage across receiver coil

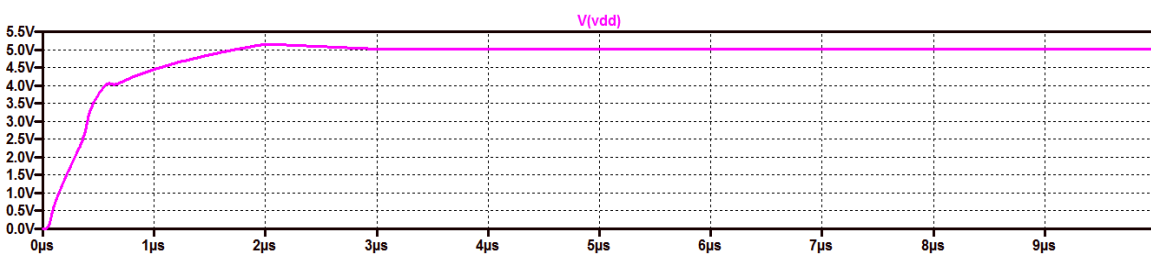


Figure 13. Rectified and regulated output voltage of transceiver with 8 pp input

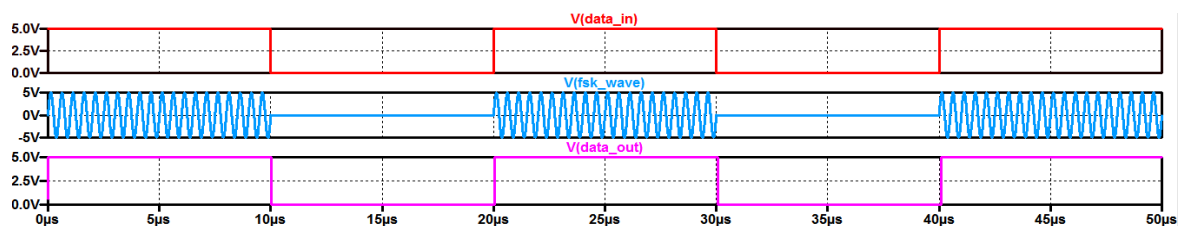


Figure 14. Data demodulated in OOK demodulation

6. CONCLUSION

The inductive link used in this work contains a 12.7 μH and a 2.4 μH transmitter coil and receiver coil respectively. Proposed On-Off Keying (OOK) transmitter consisted of digital control oscillator and class E power amplifier can transmit both data and power to the internal part of biomedical implant system over this inductive link using 2 MHz OOK carrier wave with a data rate of 1Mbps. Proposed transmitter is designed for 4.1V output voltage. The efficiency of power transfer is 42% and the power delivered to the load is about 104.7 mW. Proposed receiver consisting of voltage rectifier, voltage regulator and OOK demodulator, which voltage regulator from a rectified signal generates a stable voltage (5V) with 9mV/V line regulation. The output voltage of regulator is used as a supply voltage of other transceiver blocks (demodulator, clock generator). The proposed demodulator circuit has the ability to decode an encoded signal back to 2 MHz carrier from an OOK modulated RF input signal with 5V amplitude.

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